Renewable and Sustainable Energy Reviews 109 (2019) 294–306

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Assessment of the concentrated solar power potential in Botswana

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ARTICLE INFO

Keywords:
Bottom-up approach
Solar energy
Concentrating solar power
Land suitability
Dry-cooled PTC-type CSP technology
Renewable energy mix

ABSTRACT

A bottom-up approach that takes into account solar energy availability and land resource constraints is used to assess the technical potential for concentrating solar power (CSP) in Botswana. The CSP potential is estimated using a detailed geographical information system (GIS) based land exclusion criteria and land use data to determine land suitability in the ten districts of the country. On the basis of the national solar map of satellite-derived direct normal irradiance (DNI) information and observed DNI data combined with biogeophysical and human-induced land use constraints, it is shown that Botswana has approximately 220,016 km^2 of available land to support CSP plants. Assuming that dry-cooled parabolic trough collector (PTC)-type CSP plants are deployed, an estimated nominal capacity of 3189.54 $TWhy^{-1}$ or 363.86 GW could be accommodated by the available land area. The highest CSP potentials by district are found to be in the Central and Kgalagadi which have more than 90 GW each, collectively representing nearly half of the national potential. The largest proportion of available land relative to the district size was found to be the Southern District where more than two-thirds of the surface area was considered suitable for CSP. Based on the findings of the study, Botswana has a relatively huge CSP potential capable of exceeding the current peak energy demand by an order of a magnitude, subject to a policy framework that supports future investment in solar thermal power for a renewable energy mix as part of a climate change mitigation strategy.

1. Introduction

Over the last few decades, advances in solar energy technology have made it possible to produce power by substituting carbonaceous fuels with high temperature thermal energy from the sun. Concentrating solar power (CSP) plants make use of concentrated solar radiation to generate high pressure steam that drives a conventional steam turbine to generate electricity [1,2]. The use of concentrated sunlight to produce electricity is no doubt one of the cleanest and sustainable ways of mitigating climate change as it does not only significantly lower carbon emissions, but also reduces reliance on fossil fuels. Since the technology relies on a renewable energy resource base, it is no doubt an environmentally friendly and sustainable energy service that is capable of fostering social and economic development [3,4]. CSP plants can be equipped with thermal energy storage (TES) so as to provide dispatchable energy even when the sun is temporarily absent such as at night or during cloudy weather [5,6]. Unlike photovoltaics (PV) and hydropower, CSP plants are designed such that they can be co-fired with fossil fuels to improve dispatchability and provide baseload power, thus ensuring sustained electricity production according to demand [7,8]. Furthermore, the effects of the variability and intermittency of solar energy in CSP can be overcome by integrating the system with PV or CPV plants [9,10].

A typical CSP plant makes use of either parabolic trough collectors [11–13], parabolic dish collectors [14,15,16], linear Fresnel reflectors [17,18], or solar towers [19,20] to concentrate incoming sunlight on a relatively small target area using mirrors to produce enough thermal energy to drive a heat engine. Of the four collector systems, the parabolic trough collector (PTC) type dominates the market since it has been proven to be commercially mature due to its simplicity, easy operation and cost-effectiveness [21,22]. In addition, PTC systems are also scalable since the collector's mirror elements can be installed along a common focal line [23]. A distinctive feature of a PTC-type CSP plant is a horizontal modular array of long curved reflective mirrors disposed in parallel rows to concentrate direct normal irradiance (DNI) using a sun-tracking mechanism onto a receiver pipe or heat collection element located at the focal line of the parabolic trough surface. The heat collection element uses hot air, oil or molten salt to transfer the thermal energy to a conventional steam generator [21,24]. Unlike PV systems which are capable of converting both diffuse and direct solar radiation into electricity, CSP technology relies only on direct normal irradiance (DNI) for effective operation [25,26], thus limiting its deployment and

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https://doi.org/10.1016/j.rser.2019.04.019
Received 5 December 2017; Received in revised form 5 April 2019; Accepted 7 April 2019
Available online 19 April 2019
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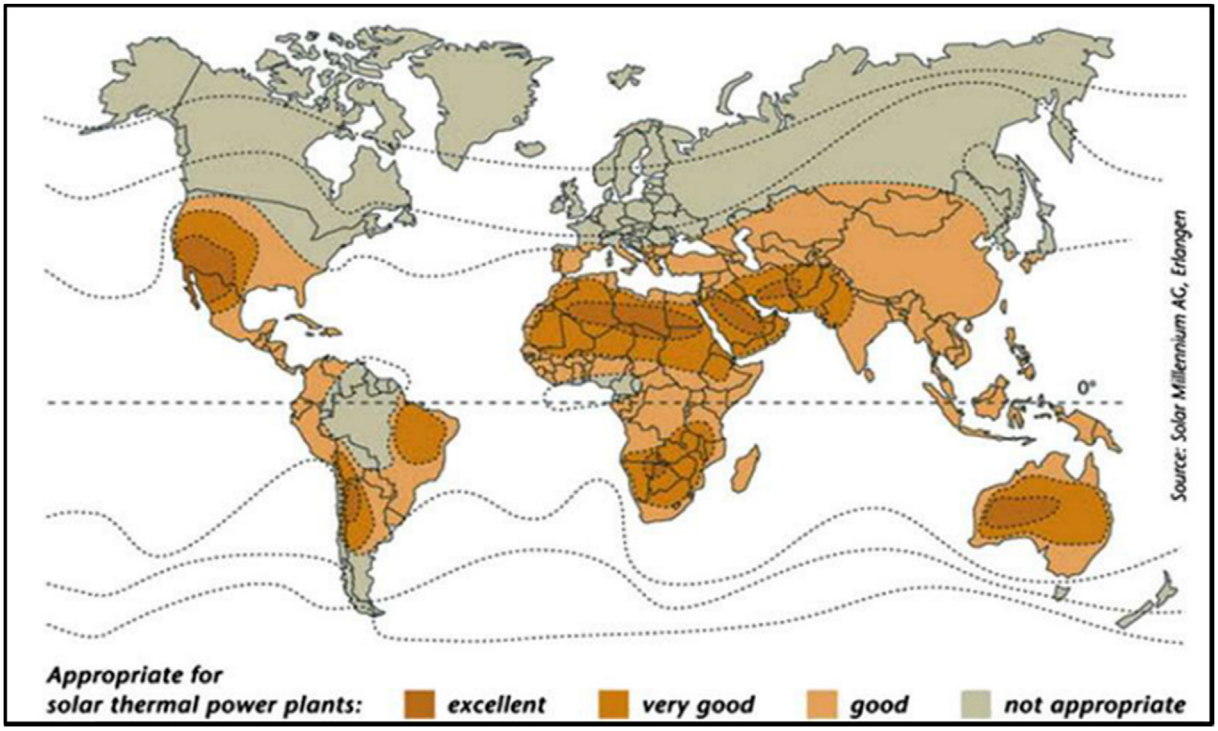

Fig. 1. The most promising areas for CSP plants (Source: Solar Millennium AG, Erlangen).

future dissemination to the subtropics between latitudes 15° and 40° where the skies are reliably clear and aerosol optical depths are low [27]. Spain and the United States of America have long taken advantage of their abundant solar and land resources and enabling economic policies to invest on CSP, and currently lead the world in terms of installed capacity, followed by India, South Africa and Morocco [28]. Africa, which boasts of the highest solar energy resource in the world and the largest available area of 12,956,360 km^2, has the highest CSP technical potential of 1,459,370 $TWhy^{-1}$ or nearly 165 TW, which represents nearly half of the global total [29]. In the south of the continent where the solar resource is relatively abundant, South Africa, with a DNI of 11,507,051 $TWhy^{-1}$ and a land area of 1,219,090 km^2 [29], the total technical CSP potential has been found to be 547.6 GW, with the highest potential sites located in the Northern Cape [30]. As one of the sunniest countries in the world, with a DNI of 5,672,081 $TWhy^{-1}$ [29], and a maximum extra-terrestrial radiation of about 43 $MJm^{-2}day^{-1}$ [31], semi-arid Botswana is well placed to benefit from CSP technology since it has a very good potential for CSP plants (Fig. 1).

An estimated 1300 million GWh of solar energy falls on the entire Botswana annually, with an average daily irradiation on a horizontal surface of 21 MJm^{-2} [32]. The number of sunny days range from 280 to 330 annually [33], and on average, 3300 sunshine hours are recorded each year [34]. The relative sparsely population of just over two million people, coupled with a land surface area of 581,730 km^2 on relatively flat terrain in the middle of the southern African plateau at a mean altitude of 1000 m make Botswana ideal for CSP. The availability of a significant portion of land that is not dedicated to any form of private, reserved or restricted land use, and with no form of visible and permanent or semi-permanent infrastructure means that adequate land is available to support CSP infrastructure. Currently, solar energy applications are limited to solar water heating in some institutional buildings and a few affluent homes, and decentralized micro-scale photovoltaic systems, albeit without any regulatory or supportive policy framework. Utility-scale power is almost entirely generated from fossil fuel energy sources, with the only state-owned 600 MW coal-fired Morupule B Power Station providing electricity to meet baseline demand. During peak periods when electricity usage is higher, two 70 MW and 90 MW diesel-fired generators located at Matshelagabedi and Orapa respectively are put into operation to augment supply into the grid [35]. Additional power supply during periods of low plant operational capacity and for off-grid border settlements is sourced from neighbouring countries through bilateral purchase agreements involving neighbouring countries within the Southern African Power Pool [36]. During the year 2017, peak demand stood at 617 MW, and this is expected to rise to nearly 700 MW by 2020 as more settlements are fed into the national electricity grid [35]. The projected growth in future energy demand has laid the basis for a national roadmap that seeks to tap into environmentally benign renewable energy sources. To that end, the National Energy Policy has been revised in the last few years to emphasize the need to develop the country into a centre of excellence for renewable energy technologies that include solar so as to reduce dependence on carbonaceous fossil fuel based electricity generation and unreliable or unguaranteed imported power [37]. The ultimate goal of the policy is to enhance electricity generating capacity through an energy mix that ensures energy security using cleaner and sustainable energy in line with the sustainable development goals of the United Nations Agenda 2030. SienrCSP has been found to promise a greater potential than PV in the provision of utility-scale power, a realistic assessment of the technical solar thermal potential is, therefore, required to support this envisaged future development.

2. Materials and methodology

2.1. Solar resource assessment

The DNI is a key factor in assessing the viability of investing in CSP technology since it determines the plant size, performance and land occupation [38]. Accurate DNI values are, therefore, an important consideration in the assessment of suitable locations of CSP plants [39]. Continental-scale and continuous long-term series of DNI are either modelled from satellite-derived data or from numerical weather prediction [40]. Uncertainties in modelled DNI data can, however, be very large since they do not always adequately take into account the effects of aerosols on radiative forcing in the atmosphere, especially in arid and

desert regions [41,42]. In Kuwait, for example, aerosol optical depth has been found to vary the surface DNI by roughly 2% due to the frequent occurrence of dust storms [43]. The DNI also depends, albeit to a lesser extent, on the quantity on the highly variable atmospheric water vapour [44] whose impact may be insignificant in semi-arid and arid regions where skies are clear for more than 90% of the time. Since ground-based measurements capture the effect of aerosol optical depth on the DNI, they are used in combination with satellite-derived data as it provides continuous temporal and spatial data and ground observations for accurate solar resource monitoring in solar power plants feasibility studies [44]. The validation of satellite-derived solar radiation covering a period of 17 years (1994–2010) using five ground observation sites in South Africa has shown a high level of data accuracy in assessing the solar resource for a site to be occupied by the Upington Solar Park in the sunniest south-western part of the country [45].

In this study, the solar resource was analysed using a data set of fourteen-year (1998–2011) yearly-averaged DNI from the national solar map developed using a SolarGIS solar model as described by Ref. [46]. The radiation map was overlain with district boundaries to create a nomenclature of each DNI land unit using three letters found in the name of the district and a numerical value added consecutively with decreasing solar irradiance. In each of the ten districts, each region with the same DNI range of values based on coloured shaded contours was identified and labelled with a code as a DNI land unit (Fig. 2). An additional small letter was added consecutively in the naming where the same unit within the district was fragmented to make it a sub-unit. The full names of the districts and their corresponding DNI land units are provided in Table 1. Ground-based averaged monthly DNI data from an online open access weather data service provided by the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) project [47] were used to validate data from the solar map. In cases where there were no ground measurements available, the average value of the DNI in the satellite-derived DNI land unit was used as a proxy for an independent determination of the CSP potential given that variations were usually very small. SASSCAL insolation values for peak sun hours were used to calculate the annual insolation value which was found to fall within the range of the DNI yearly values in each DNI land unit (Table 1). Lower-end values for the output were used to compensate for any DNI overestimates due to aerosol loading amongst other factors that tend to constrain the final plant yield. Since 1800 $kWhm^{-2}yr^{-1}$ of DNI is usually considered suitable for CSP locations if economic returns are to be realized [48–51], the whole country was found suitable for CSP plant deployment in terms of the solar resource. Since the CSP plant's electrical output potential is based on DNI measurements it varies in response to the amount of direct sunlight received over the course of a day, and there is a minimum threshold of daily direct sunlight when the plant has no net production due to constant heat losses in the solar field.

2.2. Land suitability criteria

A geographical information system (GIS) approach, combined with a satellite-derived SolarGIS radiation map of DNI range values and data from the literature were used to identify land suitability on the basis of

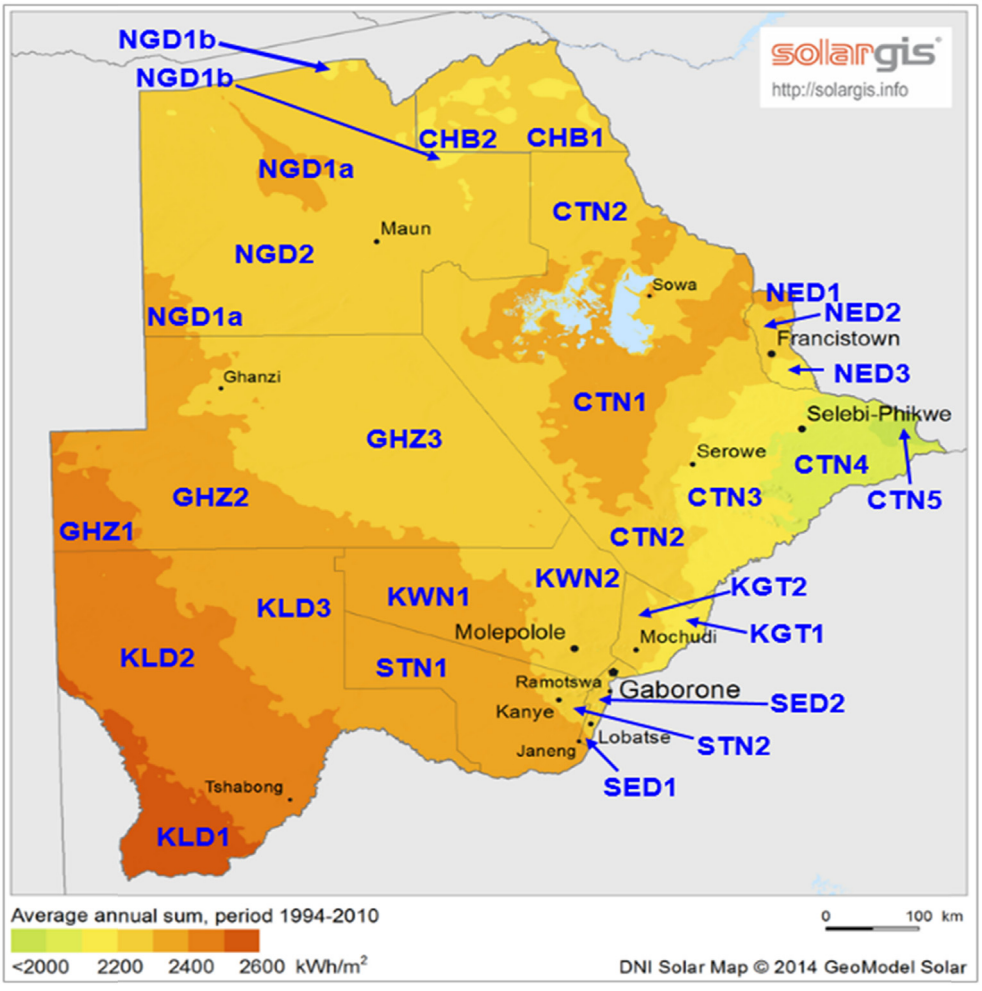

Fig. 2. Botswana DNI solar map showing the DNI land units by district.

Table 1
Botswana districts areas and their biophysical limits for CSP potential.

District			DNI land unit	DNI land unit area (km^2)	Average peak sun hours	Mean daily solar irradiance (Wm^{-2})	Mean annual DNI ($kWhm^{-2}y^{-1}$)
Central			CNT1	36,580	7.8	268	2350
			CNT2	69,490	7.7	260	2280
			CNT3	19,220	7.5	258	2264
			CNT4	14,070	8.9	234	2051
			CNT5	3230	8.9	222	1946
				142,590		**248**	**2178**
Chobe			CHB1	18,710	7.0	257	2253
			CHB2	3840	6.8	245	2148
				22,550		**251**	**2201**
Ghanzi			GHZ1	8120	7.1	255	2235
			GHZ2	36,850	7.0	268	2349
			GHZ3	72,940	7.0	257	2253
				117,910		**260**	**2279**
Kgalagadi			KLD1	19,720	5.1	291	2551
			KLD2	44,890	5.2	278	2437
			KLD3	42,330	5.7	261	2288
				106,940		**277**	**2425**
Kgatleng			KGT1	4110	5.8	257	2253
			KGT2	3850	5.8	245	2148
				7960		**251**	**2201**
Kweneng			KWN1	18,020	7.3	268	2349
			KWN2	17,870	7.2	257	2253
				35,890		**263**	**2301**
Ngamiland			NGD1a	25,480	7.5	268	2349
			NGD1b	1970	7.7	266	2332
			NGD2	79,880	7.6	256	2244
			NGD3a	2950	8.5	245	2148
			NGD3b	1370	8.1	242	2121
				111,650		**255**	**2239**
North-East			NED1	1290	7.5	268	2349
			NED2	2990	7.6	257	2253
			NED3	1710	7.5	245	2148
				5990		**257**	**2250**
South-East	SED1	370	5.3	268	2349		
	SED2	1410	5.6	253	2218		
		1780		**261**	**2284**		
Southern	STN1	25,120	5.4	268	2349		
	STN2	3350	5.3	257	2253		
		28,470		**263**	**2301**		
TOTAL		**581,730**	**6.9**	**259**	**2266**		

a defined land exclusion criteria as described by Refs. [30,52–57]. The various biophysical and socio-economic constraints shown in Fig. 3 exclude the following: 1) very sensitive natural areas; 2) slope > 3%; 3) marshes, swamps and extensive floodplains; 4) salt pans and permanent water bodies such lakes and artificial reservoirs; 5) mobile dunefields; 6) drainage lines; 7) land dedicated to biodiversity protection or conservation such as national parks, game sanctuary and forest reserves; 8) regularly cultivated agricultural areas; 9) fenced freehold and leasehold ranches or farms; 10) heavily built-up areas such as settlements; 11) infrastructural developments such as roads, reliable water supply systems, telecommunication and power transmission lines, 12) large restricted access areas such as military camps, minefields, monuments and airports.

In cases where GIS was not applicable and there was no documented information on the sizes of the land use categories or biophysical features, estimations had to be made in relation to sizes of documented land use categories using cartographic analysis. Since CSP technology is land intensive, with less than one square kilometer of land typically yielding no more than 2 MW in existing plants, features not readily detectable on cartographic or GIS-derived maps, or not mentioned in working policy documents, on account of being insignificant in terms of the surface area were excluded in the calculation. Such features, which included stand-alone hills, minor drainage lines, detached infrastructural developments, small agricultural holdings and isolated communication installations contributed less than 0.1% to the geographical potential. The total land available for large-scale CSP installation, which was free from biophysical and land use constraints, was obtaining after excluding the surface area deemed unsuitable or unavailable for CSP plant occupation. Once the seemingly suitable land was identified, the next step was to subject it to an accessibility criteria as explain in the next section.

2.3. Land accessibility

Remote places which may be biogeophysically suitable for CSP may be too far from roads, transmission lines, settlements and/or human land use, thus attracting some additional costs to make them easily reachable. Easy access to CSP plants is required for transport of materials to the site for reparation and mirror washing as part of the routine maintenance for the plants. Under the assumption that the introduction of new access roads and infrastructure to parts of the country that are either uninhabited, devoid of precious natural resources, or lack significant socio-economic value due to other competing development needs was unlikely, DNI land units or parts thereof, which are more than 50 km from any form of land use, major infrastructural corridor or human occupation were considered inaccessible, and therefore, unavailable. Once the accessible land areas have been identified as available land (Fig. 4), technical factors that include land use efficiency, plant efficiency under certain ambient environmental conditions and the type of cooling technology had to be considered.

2.4. Land use factor

Vast tracts of land are required for the solar field, the power block

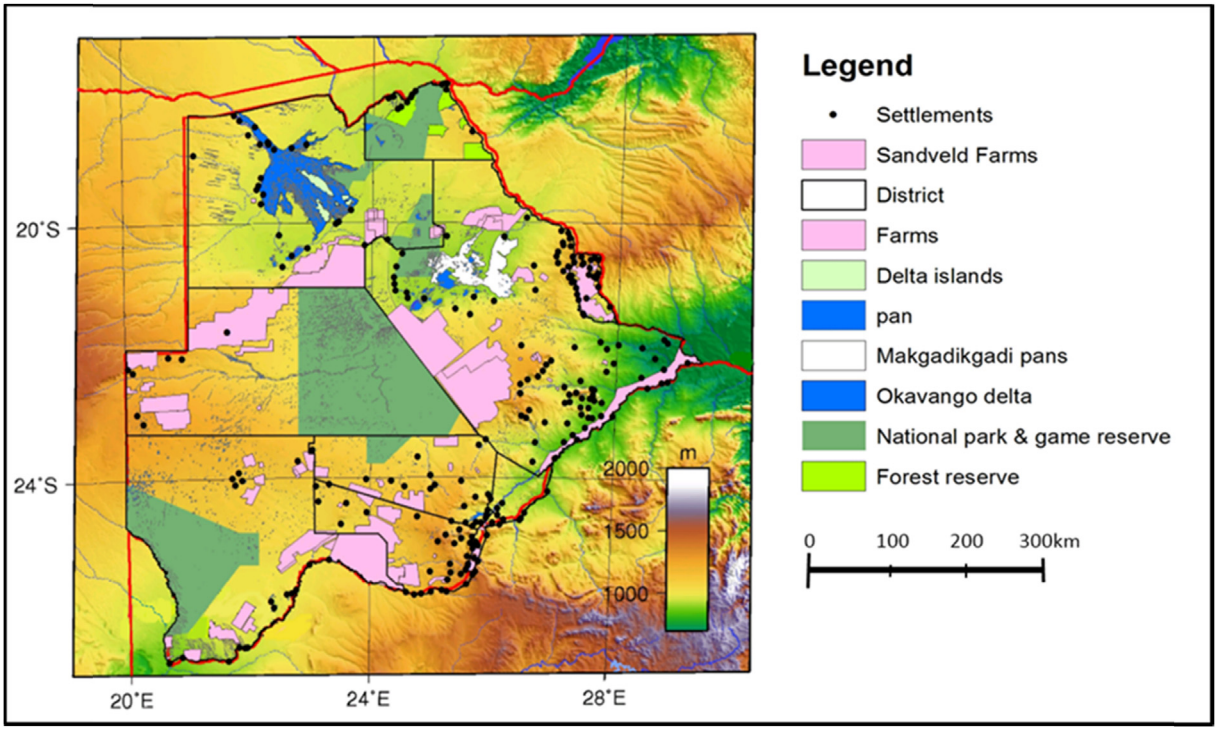

Fig. 3. The elevation map of Botswana CSP showing some major biophysical and land use constraints. Relief map used has been uploaded into the public domain without any copyright restrictions.

and the thermal storage facility if it is to be used. The land use factor, which is the aperture area of reflectors divided by the total land area required for occupation [58], is determined as the ratio of the actual area (occupied by the solar field, the storage component if available, and the power block) to the total land area [38,58,59]. A two land-use metrics as defined by Ref. [59] identifies the total area, which corresponds to all land enclosed by the site boundary which is typically fenced or protected and the direct impact area which comprises land directly occupied by solar arrays, access roads, substations, service buildings, and other infrastructure. The solar field takes up most of the

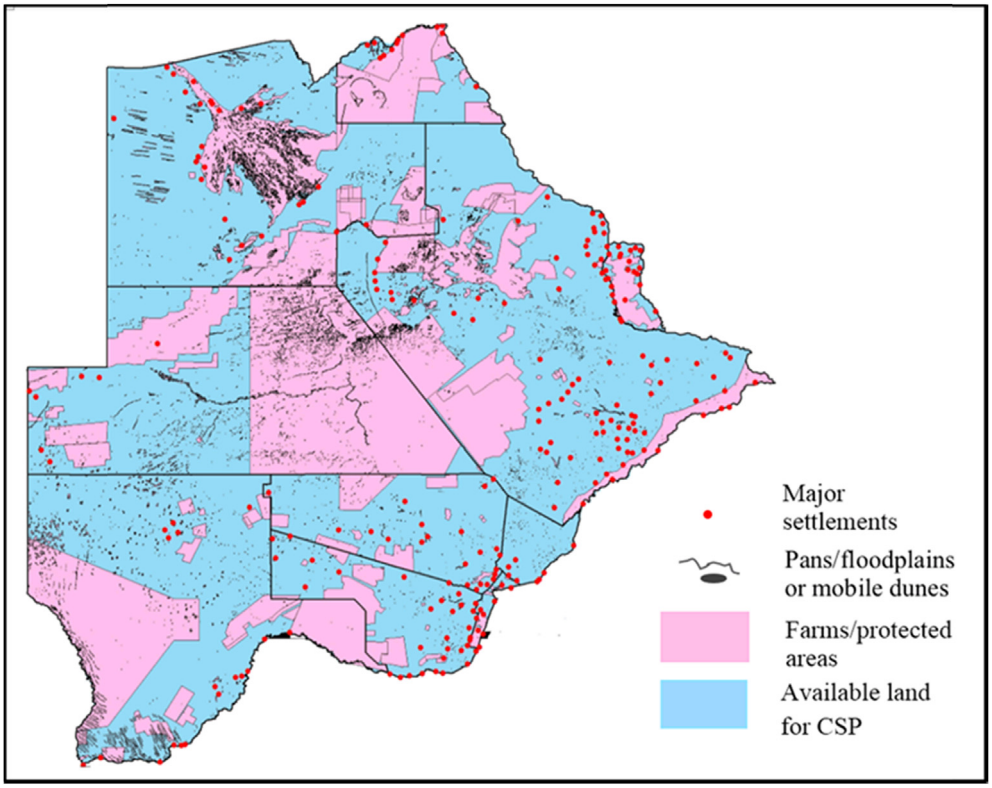

Fig. 4. Major land cover and land use constraints and resulting available land for CSP.

Table 2
Botswana districts areas and their biophysical limits for CSP potential.

SASSCAL weather station	DNI Land Unit	Monthly average maximum temp (°C)	Number of days in a year when average temp exceeds 32.0 °C[a]	Number of days in a year when daily mean temp exceeds 32.0 °C[a]	Average monthly wind speed for 90% of the time[a] (ms^{-1})	Maximum recorded wind gusts in a month[a] (ms^{-1})	Estimated CSP plant power output reduction (%)
Central	CNT1	33.2	134	37	1.9	7.4	4.5
	CNT2	33.4	122	34	1.7	9.3	4.0
	CNT3	33.5	111	33	1.8	8.5	3.5
	CNT4	33.0	124	35	1.6	7.7	4.0
	CNT5	32.8	128	36	1.7	7.8	4.0
		33.2	**124**	**35**	**1.7**	**8.1**	**4.0**
Chobe	CHB1	32.2	108	36	1.6	7.0	**3.0**
	CHB2	31.8	137	36	1.7	7.9	**5.0**
		32.0	**123**	**36**	**1.7**	**7.5**	**4.0**
Ghanzi	GHZ1	31.2	137	39	1.6	8.3	**5.0**
	GHZ2	31.4	142	38	1.6	8.4	**5.0**
	GHZ3	31.3	148	40	1.8	8.7	**5.5**
		31.3	**142**	**39**	**1.7**	**8.5**	**5.2**
Kgalagadi	KLD1	31.6	145	40	1.0	10.2	**5.5**
	KLD2	31.9	141	39	0.9	10.4	**5.5**
	KLD3	32.1	140	39	0.8	10.0	**5.5**
		31.9	**142**	**39**	**0.9**	**10.2**	**5.5**
Kgatleng	KGT1	32.0	112	37	0.7	6.9	**3.0**
	KGT2	32.4	116	36	0.6	7.1	**3.0**
		32.2	**114**	**37**	**0.7**	**7.0**	**3.0**
Kweneng	KWN1	32.7	120	38	0.7	7.7	**4.0**
	KWN2	32.2	113	37	0.8	7.2	**3.5**
		32.5	**117**	**38**	**0.8**	**7.5**	**3.8**
Ngamiland	NGD1a	32.9	145	40	1.9	7.6	**5.5**
	NGD1b	32.7	136	39	1.8	7.7	**5.0**
	NGD2	33.5	133	38	1.8	7.9	**5.0**
	NGD3a	33.6	132	39	1.7	7.3	**5.0**
	NGD3b	32.7	138	39	1.8	7.4	**5.0**
		33.1	**137**	**39**	**1.8**	**7.6**	**5.1**
North-East	NED1	33.4	122	37	1.6	6.4	**4.0**
	NED2	33.7	125	38	1.8	6.1	**4.0**
	NED3	33.9	118	36	1.8	6.0	**3.5**
		33.7	**122**	**37**	**1.7**	**6.2**	**3.8**
South-East	SED1	32.9	116	35	0.8	5.3	**3.0**
	SED2	33.1	115	35	1.1	5.7	**3.0**
		33.0	**116**	**35**	**1.0**	**5.5**	**3.0**
Southern	STN1	32.4	113	37	1.5	6.3	**3.5**
	STN2	32.8	104	35	1.3	6.0	**3.0**
		32.6	**109**	**36**	**1.4**	**6.2**	**3.3**
TOTAL		**32.6**	**125**	**37**	**1.3**	**7.4**	**4.0**

[a] Temperature and wind data for the period 2005–2017.

direct impact area, and consists of solar energy collectors which are sufficiently well spaced to minimize shadows and to allow passage for the maintenance of the big curved reflecting mirrors, and solar receivers which absorb and convert the concentrated solar to heat for the power block [38]. The remaining direct impact area accommodates the power block and where required, a TES facility. Depending on the thermal storage technology used, the energy storage infrastructure typically consists of energy storage tanks, thermocline systems or steam accumulators [60]. Modelled results of a typical parabolic trough system with thermal storage in desert areas where there are increased parasitic losses for storage and larger collector fields put a land use factor of between 25% and 40% [58]. Where land use is optimized, a high-end value of 40% is used in the study to indicate that of the total fenced area, only 40% of the enclosed land is actually taken up by the plant.

2.5. Land use efficiency

Solar-to-electric efficiency: In the solar field, not all solar energy incident on the collector surfaces will be converted to electricity. Depending on the solar collector type, only a small percentage of the total energy that falls on the collector will be converted to electricity. The percentage of solar energy converted to electricity in solar power plant defines the solar-to-electric efficiency, and typically ranges from 15% to 25% depending on the solar collector type, with state-of-the art PTC-type systems having an average efficiency of 15% [52]. However, modelled results of a typical parabolic trough system with TES in desert areas put the net efficiency in the range of 11–16% [58]. In the case of Botswana, the deployment of the recommended dry cooling technology gives a slightly higher but somewhat conservative solar-electric efficiency of 12% or 0.12 to account for uncertainties associated with the resolution of DNI data. In the unlikely event of the solar-to-electric efficiency being lower than 12%, the solar field could be oversized to compensate for the deficit.

Land use efficiency: Land use efficiency is a product of the solar-to-electric efficiency and the land use factor, which is the aperture area of reflectors divided by the total land area required for occupation [58]. In mid-latitude Canada, for example, where the DNI has a lower range of between 1500 $kWm^{-2}y^{-1}$ and 1900 $kWm^{-2}y^{-1}$, a conservative solar-to-electric efficiency of 11% and a land use factor of 35% were used to estimate the technical potential of PTC-type CSP [55]. In the case of Botswana, which has a relatively higher DNI, the land use efficiency is the product of the land use factor (0.4) and the solar-to-electric efficiency (0.12) which is 0.048.

2.6. Environmental parameters and plant efficiency

Reduction in CSP plant efficiencies become noticeable when

ambient temperatures exceed 32 °C [61]. Monthly maximum temperatures in Botswana range from 26 °C during the mid-winter month of July to nearly 37 °C during the peak summer from November to February. In all the DNI land units, during peak sun hours, which ranged from five to nine in a given day, maximum temperatures exceeded 32 °C between 240 and 270 days annually, depending on the location and time of the year, according to meteorological records. Significant energy efficiency losses of between 5% and 10% are experienced when the ambient temperatures rise above 37.7 °C [62] which occur on average, between forty and fifty days on any given year during peak sun hours in mid-summer (November–February) over most parts of the country in the last five years. Since the number of days when maximum temperatures exceed 37.7 °C represent less than 15% of all the days in any given year in most of the districts, it is less likely that efficiency losses would exceed 5% for most of the time, hence a conservative decrease in the energy yield of the PTC plant was capped at a low end value of 5.0%. Any assumed increases in plant efficiency losses beyond 5.0% would more likely underestimate the full technical potential of CSP, given that the solar field could be oversized to compensate for any anticipated trade-offs. Since mean daily peak sun ambient temperatures vary across the country wherein they are higher in some districts and lower in others during the hot season, the variations tend to be compensated by a reversal during the winter, so that an average, spatial variations of ambient temperatures may be regarded to be the same on a year-long basis. The 5% decrease in plant efficiency was, therefore, applied for all the districts in the calculation of the annual CSP output. In terms of wind speed, normal operation for PTC-type CSP plants require windspeeds of less than 7 ms^{-1}, beyond which optical efficiency loss may occur, largely because of dust and debris accumulation on the concentrators [63,64], and possibly, structural damage [63–65]. In Botswana, since monthly windspeeds range between 0.6 ms^{-1} and 3.0 ms^{-1} for 90% of the time, with occasional gusts seldom exceeding 7 ms^{-1} on any given day (Table 2) during extreme weather, the wind effect was considered to be of little effect on plant performance.

2.7. Water availability

The water demand for dry cooling is approximately 300 m^3 per GWh, whilst wet-cooled and hybrid plants need up to 1300 m^3 and 3300 m^3 of water for every GWh respectively [62,66–70]. Since water availability could constrain large-scale CSP expansion in dry and semi-dry locations, dry-cooling technology is recommended to give greater flexibility in terms of location. In comparison with the wet-cooled CSP plants, the dry-cooled type reduce water demand by as much as 90% [8] since a minimal amount of water is only required for steam make-up, mirror washing and some miscellaneous uses [67,70]. Dry cooling of CSP plants are suitable for regions with a dry climate and haev been found to be economically and tecnhically feasible in desert regions [71]. The use of dry-cooled CSP plants also eliminate environmental concerns emanating from evaporative water treatment to remove particulates and salts by draining some cooling water, which is a potential environmental hazard due to the high concentration of salts, and ambient air pollution [67]. The only major downside of the dry-cooling technology is the energy output reduction by between 3% and 10% on an annual basis, resulting in increased electricity cost [62,66,67,68,70]. In this study, a worst case scenario was assumed by using a high-end value of 10% or 0.1. The trade-offs in terms of plant power losses are, however low when compared to the benefits of operating the plants in drier sites with relatively better solar resources.

3. Calculation of the CSP technical potential

The solar resource availability, when used alone, determines the theoretical potential of CSP. The theoretical potential is modified by biophysical and socio-economic factors to give the geographical potential. Once the CSP plant is in operation, other factors come into play, such as the capacity factor, the cooling technology and the levelized cost of electricity (LCOE), further reducing the value to define the technical economic potential. The value of the latter potential is difficult to calculate since the capacity factor is difficulty to determine until the plant is in full operation. Realistic planning of a PTC-type CSP plant is, therefore, based on the technical potential, which takes into account the solar resource, land availability and accessibility, solar-to-electric efficiency and the desired plant configuration. A simplified basic mathematical formula that requires only the DNI, the total available area and the land use factor has been developed by Ref. [72] for calculating the CSP potential in Africa. On the basis of the prescribed formula, the annual CSP technical potential (in $kWhy^{-1}$) of an PTC-type plant is a product of the local solar resource, Ω, defined by the mean annual DNI (in $kWhm^{-2}y^{-1}$), multiplied by the total land occupation area, Y (in m^2), the land use efficiency, θ, and the overall annual plant output due to dry cooling, θ, so that.

$$CSP = \Omega * Y * \theta * \delta$$

4. Results and discussion

Botswana is a sub-tropical country endowed with abundant solar resource in which the DNI is in excess of 1900 $kWm^{-2}y^{-1}$, with relatively large tracts of available land spreading over an area of 220,016 $km^{2,}$ which is just more than a third of the total natural surface area. A combination of ground and satellite-derived data in all the districts show an average DNI ranges between 1950 $kWm^{-2}y^{-1}$ and 2,550 k $Wm^{-2}y^{-1}$, with highest values in the Kgalagadi District in the south-west of the country. Major land use constraints that include biodiversity protected areas, ranches, settlements, drainage lines and sand dunes were found to contribute significantly to the proportion of unavailable land (Fig. 4). Rough terrain was found to be the major biophysical constraint in north-eastern, south-eastern and some isolated parts of central Botswana. The geographical potential of the commercially proven parabolic trough collector (PTC) type concentrating solar power (CSP) plants with a solar-to-electric efficiency ranging from 0.12 and a land use factor of 0.4, was calculated to give a technical potential of 3189.54 $TWhy^{-1}$ or 363.86 GW (Table 3). The calculated available area (220,016 km^2) is slightly lower than the 265,409 km^2 by 17% as given by Ref. [72], and the technical potential is nearly four times smaller than the 13,070 $TWhy^{-1}$ [72]. The disparity in the sizes of the available land area could be attributed to the fact that current land use and infrastructural developments since the calculation is based on the land resource available more than a decade ago. Since Botswana is a rapidly growing economy which has an effect on the land use, the technical potential is bound to change to decrease as land availability is decreased. Technical constraints on plant operation such as the effect of peak sun temperature on plant efficiency, the land use factor, and plant cooling technology must also be taken into account when calculating the effective potential, and since these are not indicated in the literature, they were most possibly not included in the calculation. On the basis of the solar, land and technical constraints presented in this paper, the highest potentials were found in the Central and Kgalagadi districts, which together constituted nearly half of the available land and just below half of the national CSP potential on account of less conserved or occupied land. Major land use constraints such as protected areas that include national parks, game reserves and forest reserves occupy a significant land area in northern, central, and western Botswana where they take up at least a third of the total land area. The proportion of land available for CSP was found to be lowest in the Chobe, Ngamiland and South East districts where available land covered less than one fifth of the individual districts' surface area. Apart from naturally occurring sensitive ecosystems which are protected by law, cattle ranches and commercial agricultural farms occur in most parts of the country presented the major human-related constraints. Settlements and supporting communication infrastructure such as road networks, power

Table 3
Estimated CSP potentials by district in Botswana.

District	Total area ($\times 10^6 m^2$)	Average DNI (kWh m^{-2})	Land Available for CSP ($\times 10^6 m^2$)	% land available	CSP Potential ($TWhy^{-1}$)	CSP Potential (GW)
Central	142,590	2178	57,261	40	790.1	90.1
Chobe	22,550	2201	343	2	4.8	0.5
Ghanzi	117,910	2279	42,690	36	603.2	68.8
Kgalagadi	106,940	2425	53,868	50	787.5	89.8
Kgatleng	7960	2201	4686	59	63.8	7.3
Kweneng	35,890	2301	21,119	59	298.5	34.0
Ngamiland	111,650	2239	17,943	16	249.3	28.4
North-East	5990	2250	2703	45	43.6	5.0
South-East	1780	2284	278	16	4.7	0.5
Southern	28,470	2301	19,125	67	344.0	39.2
TOTAL	**581,730**	**2266**	**220,016**	**38**	**3189.54**	**363.86**

Table 4
Botswana districts areas and their biophysical limits for CSP potential.

District	Surface area (km^2)	DNI land unit	DNI land unit area (km^2)	Hills or rough terrain (km^2)	Natural lakes, swamps and pans (km^2)	Mobile and/or active dunes (km^2)	Drainage lines (km^2)	Total areal coverage (km^2)
Central	142,590	CNT1	36,580	6	16,058	0	14	16,078
		CNT2	69,490	78	16	0	22	116
		CNT3	19,220	300	33	0	41	374
		CNT4	14,070	60	5	0	11	76
		CNT5	3230	22	0	0	4	26
			142,590	466	16,112	0	92	16,670
Chobe	22,550	CHB1	18,710	0	179	0	13	192
		CHB2	3840	0	0	0	3	3
			22,550	0	179	0	16	195
Ghanzi	117,910	GHZ1	8120	0	11	0	0	11
		GHZ2	36,850	0	10	0	0	10
		GHZ3	72,940	0	11	0	0	11
			117,910	0	32	0	0	32
Kgalagadi	106,940	KLD1	19,720	0	3	536	0	539
		KLD2	44,890	0	8	2212	0	2220
		KLD3	42,330	0	21	0	0	21
			106,940	0	32	2748	0	2780
Kgatleng	7960	KGT1	4110	64	0	0	2	66
		KGT2	3850	11	0	0	3	14
			7960	75	0	0	5	80
Kweneng	35,890	KWN1	18,020	0	8	0	0	8
		KWN2	17,870	286	0	0	4	290
			35,890	286	8	0	4	298
Ngamiland	111,650	NGD1a	25,760	0	0	0	0	0
		NGD1b	1970	0	0	0	0	0
		NGD2	79,600	6	496	0	12	514
		NGD3a	2950	0	0	0	0	0
		NGD3b	1370	0	0	0	0	0
			111,650	6	496	0	12	514
North-East	5990	NED1	1290	6	0	0	3	9
		NED2	2990	60	0	0	26	86
		NED3	1710	12	0	0	4	16
			5990	78	0	0	33	111
South-East	1780	SED1	370	92	0	0	2	94
		SED2	1410	2	0	0	6	8
			1780	94	0	0	8	102
Southern	28,470	STN1	25,120	0	0	0	0	0
		STN2	3350	130	0	0	4	134
			28,470	130	0	0	4	134
TOTAL	**581,730**		**581,730**	**1135**	**16,859**	**2748**	**174**	**20,916**

lines and water transfer lines occur mostly in the eastern half of the country where more than half of the population live, work and cultivate land. Natural land constraints such as rough terrain that include low-lying hills in the eastern part of the country and active sand dunes in the south-west of the country present notable biophysical barriers. Hilly terrain occupies the greater area of the smaller districts such as the North-East and the South-East, where cattle ranches occupy most of the land. The Southern District has the largest proportion of land available since it has fewer land use constraints and biophysical barriers relative to its size. The various biophysical and socio-economic constraints of each district and the total CSP potential are provided below.

Central District (142,590 km^2): Multiple land uses that include ranches, settlements and associated major communication and water provision infrastructures, together with the vast Makgadikgadi Salt Pans, collectively occupy a significant land area [73,74]. In the eastern part of the district, the Makgadikgadi Salt Pans (16,058 km^2) in CNT1, hill ranges in all DNI land units except CNT1, and extensive drainage lines in all the DNI land units excluded at least 16,670 km^2 of land (Table 4). Land use zones that included wildlife protected areas, commercial ranches, and periodically cultivated arable land claimed a significant

Table 5
Botswana districts and their human-induced constraints for CSP potential.

District	DNI land unit	DNI land unit area (km^2)	Protected and/or conserved area (km^2)	Farms/ranches (km^2)	Arable land (km^2)	Settlements, supporting infrastructure and artificial reservoirs (km^2)	Total areal coverage (km^2)
Central	CNT1	36,580	978	5852	398	686	7914
	CNT2	69,490	3098	21,886	1664	438	27,086
	CTN3	19,220	80	5420	1667	2030	10,197
	CNT4	14,070	220	4495	444	255	5414
	CNT5	3230	140	440	94	18	692
		142,590	4516	38,093	4267	4427	51,303
Chobe	CHB1	18,710	11,230	230	48	43	11,551
	CHB2	3840	3577	0	0	0	3577
		22,550	14,807	230	48	43	15,128
Ghanzi	GHZ1	8120	0	3529	0	34	3563
	GHZ2	36,850	4185	6699	0	92	10,976
	GHZ3	72,940	43,216	4995	0	54	48,265
		117,910	47,401	15,223	0	180	62,804
Kgalagadi	KLD1	19,720	7474	2570	0	44	10,088
	KLD2	44,890	20,364	2018	0	72	22,454
	KLD3	42,330	0	10,584	0	96	10,680
		106,940	27,838	15,172	0	212	43,222
Kgatleng	KGT1	4110	0	0	1117	33	1150
	KGT2	3850	0	0	1421	73	1494
		7960	0	0	2538	106	2644
Kweneng	KWN1	18,020	1112	1737	148	185	3182
	KWN2	17,870	1480	882	751	73	3186
		35,890	2592	2619	899	258	6368
Ngamiland	NGD1a	25,760	22,866	0	150	266	23,282
	NGD1b	1970	0	0	0	0	0
	NGD2	79,600	5505	12,006	339	144	17,994
	NGD3a	2950	0	0	0	0	0
	NGD3b	1370	270	0	0	0	270
		111,650	28,641	12,006	489	410	41,546
North-East	NED1	1290	0	0	168	173	341
	NED2	2990	0	1533	42	204	1779
	NED3	1710	0	985	56	15	1056
		5990	0	2518	266	392	3176
South-East	SED1	370	0	272	0	4	276
	SED2	1410	52	754	81	237	1124
		1780	52	1026	81	241	1400
Southern	STN1	25,120	190	6239	1666	141	8236
	STN2	3350	0	0	790	185	975
		28,470	190	6239	2456	326	9211
TOTAL	**581,730**	**126,037**	**93,126**	**11,044**		**6505**	**236,802**

portion of the less populated land. The major land uses, together with artificial reservoirs in the eastern part of the district, settlements and associated infrastructural corridors, mine concessions, camps and airports occupy a total of 51,303 km^2 of the district (Table 5). The inaccessibility of 17,356 km^2 of land closer to Chobe District in the northern part of the district increases the area of unavailable land to 85,329 km^2, so that only 57,261 km^2 or roughly 40% is available land for CSP installation (Table 6). The available land in the whole district yields an estimated CSP potential of 790.1 $TWhy^{-1}$ or approximately 90.1 GW (Table 7).

*Chobe District (22,*550 km^2*):* The district is primarily a biodiversity conservation area, with the Chobe National Park, which extends into the adjacent Ngamiland District, occupying nearly half of the total surface area [75,76]. The inhabitable Chobe Swamps and some active and relict drainage lines are the only major biophysical constraints that cover 195 km^2 (Table 1). The Chobe National Park (10,896 km^2), six forest reserves (3577 km^2), the Pandamatenga Farms (230 km^2), mixed farmlands (48 km^2), settlements and associated infrastructural corridors (43 km^2) exclude 14,794 km^2 of the district an account of human land use (Table 2). Inaccessibility of roughly 7218 km^2 in the vicinity of the Chobe swamps and the vicinity of the wildlife protected area which provides wildlife migratory corridors in the two land units ensure that 22,207 km^2 is unavailable, so that only 343 km^2 or 2% as available land for CSP (Table 3). The available land yields a total CSP potential of only 4.8 $TWhy^{-1}$ or 500 MW (Table 4), which is enough to meet current national peak demand, and also approximately equal to the installed capacity of the existing coal-fired power plant.

*Ghanzi District (117,*910 km^2*):* Nearly half of the district is occupied by the largest wildlife protected area, namely Central Kalahari Game Reserve (CKGR) in the east, whilst the Ghanzi Block farms take up a significant area in the north-west [77]. Relict drainage lines and some ephemeral pans biophysically excluded a total of 32 km^2 within the district (Table 4). The CKGR (of which the larger area of 48,122 km^2 is in GHZ3), commercial farms, settlements and associated infrastructural corridors (168 km^2) presented the largest constraints in the district to exclude some area of 62,804 km^2 (Table 5). Given that approximately 12,384 km^2 was considered inaccessible, a total of 75,220 km^2, which is approximately two-thirds of the district, was excluded, so that only 42,690 km^2 or 36% was found available for CSP (Table 6) with a technical potential of 603.2 $TWhy^{-1}$ or approximately 68.8 GW of CSP (Table 7).

*Kgalagadi District (106,*940 km^2*):* Wildlife conservation and pastoral farming are the major land uses in the district, with the Kalahari Transfrontier Park (28,509 km^2) occupying most of the district [78]. Mobile dune-fields in KLD1 and KLD2, and pans, most of which occur in KLD2 and KLD3, biophysically excluded some 2748 km^2 of the district (Table 4). An area of roughly 7040 km^2 within the district considered inaccessible on account of being too far from settlements and major land uses which are concentrated in the south, south-eastern eastern and northern parts of the district. The Kalahari Transfrontier Park (of which 20,364 km^2 lies in KLD2), several fenced commercial farms, and settlements and supporting infrastructure occupy an estimated total

Table 6
Botswana districts and their total geographical physical limits for CSP potential.

District	Surface area (km^2)	DNI land unit	Bio-physically exclusion area (km^2)	Human induced exclusion area (km^2)	Inaccessible land area (km^2)	Total exclusion area (km^2)	Available area (km^2)
Central	142,590	CNT1	16,078	7914	2140	26,132	10,448
		CNT2	116	27,086	15,216	42,418	27,072
		CTN3	374	10,197	0	10,571	8649
		CNT4	76	5414	0	5490	8580
		CNT5	26	692	0	718	2512
			16,670	**51,303**	**17,356**	85,329	57,261
Chobe	22,550	CHB1	192	11,217	6958	18,367	343
		CHB2	3	3577	260	3840	0
			195	**14,794**	**7218**	22,207	343
Ghanzi	117,910	GHZ1	11	3563	1100	4674	3446
		GHZ2	10	10,976	6384	17,370	19,480
		GHZ3	11	48,265	4900	53,176	19,764
			32	**62,804**	**12,384**	75,220	42,690
Kgalagadi	106,940	KLD1	539	10,118	640	11,297	8423
		KLD2	2220	22,454	3740	28,414	16,476
		KLD3	21	10,680	2660	13,361	28,969
			2780	**43,252**	**7040**	53,072	53,868
Kgatleng	7960	KGT1	66	1150	0	1216	2894
		KGT2	14	1494	550	2058	1792
			80	**2644**	**550**	3274	4686
Kweneng	35,890	KWN1	8	3182	5454	8644	9376
		KWN2	290	3186	2651	6127	11,743
			298	**6368**	**8105**	14,771	21,119
Ngamiland	111,650	NGD1a	0	23,282	0	23,282	2198
		NGD1b	0	0	1970	1970	0
		NGD2	514	17,994	45,627	64,135	15,745
		NGD3a	0	0	2950	2950	0
		NGD3b	0	0	1370	1370	0
			514	**41,276**	**51,917**	93,707	17,943
North-East	5990	NED1	9	341	0	350	940
		NED2	86	1779	0	1865	1125
		NED3	16	1056	0	1072	638
			111	**3176**	**0**	3287	2703
South-East	1780	SED1	94	276	0	370	0
		SED2	8	1124	0	1132	278
			102	**1400**	**0**	1502	278
Southern	28,470	STN1	0	8236	0	8236	16,884
		STN2	134	975	0	1109	2241
			134	**9211**	**0**	9345	19,125
	581,730		**20,916**	**236,228**	**104,570**	**361,714**	**220,016**

area of 43,222 km^2 (Table 5). The biophysical and land use constraints, combined with the inaccessible area, excluded 53,072 km^2 or nearly half of district land area, so that 53,868 km^2 of available land (Table 6) that could support a CSP potential of 787.5 $TWhy^{-1}$ or 89.8 GW (Table 7).

Kgatleng District (7960 km^2): The district is largely dedicated to mixed farming and human occupation, as well as supporting infrastructure [79]. Hilly terrain, most of which is in the centre of the district in KGT1 and some active drainage lines excluded an area of 79 km^2 (Table 4). Seasonally or periodically cultivated land, together with the Bokaa Dam (7 km^2) as well settlements and associated infrastructural corridors constrained 2644 km^2 of the land area (Table 5). Since only 550 km^2 of land located just after the confluence of Monametsana and Notwane rivers in KGT2 was considered inaccessible, a total of 3274 km^2 was found to be excluded by biophysical and land use constraints, so that 4686 km^2 or nearly 60% of the land area was available (Table 6). As a result, the district has an estimated total CSP potential of an estimated 63.8 $TWhy^{-1}$ or 7.3 GW (Table 7).

*Kweneng District (35,*890 km^2*):* Wildlife protection agriculture and livestock farming, all of which are practised in a biophysically diverse environment, are the major land uses in the district [80]. Low-lying hill ranges in the eastern part of the district (KWN2), ephemeral pans in the western part of the district (KWN1), and drainage lines in KWN2 presented the major biophysical constraints which excluded 298 km^2 of land (Table 4). Khutse Game Reserve (2592 km^2), of which the major part with an area of 1480 km^2 lies in KWN2, fenced ranches and farms, most of which occupy KWN1, arable land with mixed farming, settlements and associated infrastructure that includes monuments and heritage sites covered 6368 km^2 (Table 5). Since an area of 8105 km^2 that includes the extreme north-western part of district in KWN1 and northern KWN2 was considered inaccessible, a combined area from the various constraints was estimated at 14,771 km^2 (Table 6). As a result, the district had 21,119 km^2 of available land, which was enough to yield a CSP potential of 298.5 $TWhy^{-1}$ or 34.0 GW (Table 7).

*Ngamiland District (111,*650 km^2*):* According to the Ngamiland District Development Plan 6 2003–2009 [81,82], the district is ecologically the most diverse in the country, with a sizeable part of it being mainly dedicated to biodiversity conservation, wildlife protection and pastoral farming. The seasonally flooded Lake Ngami (240 km^2), ephemeral pans (256 km^2) in the south-west, drainage lines in the west and some hills in the south, biophysically excluded some 514 km^2 of land (Table 4). The total protected area of the Okavango Delta (22,866 km^2), the combined wildlife protected areas outside the delta (5444 km^2), Hainaveld commercial farms (12,006 km^2), arable land, settlements and associated major infrastructural corridors and some heritage sites excluded 41,546 km^2 (Table 5). The inaccessible NGD1a, NGD1b and NGD3a increased the excluded area by 51,917 km^2 (Table 6). As a result, 93,707 km^2 or more than 84% of the district land area was unavailable, so that only 17,943 km^2 could accommodate CSP with an estimated potential of 249.3 $TWhy^{-1}$ or 28.4 GW (Table 7).

Table 7
Calculated CSP potentials of the various DNI land units in Botswana.

District	Land area (km^2)	DNI Land Unit	Available area (x $10^6 m^2$)	% land availability	Theoretical CSP Potential ($10^{12} kWhy^{-1}$)	Effective CSP Potential ($TWhy^{-1}$)	Effective CSP Potential (GW)
Central	142,590	CNT1	10,448	29	0.178	170.04	19.40
		CNT2	27,072	39	0.386	370.52	42.27
		CNT3	8649	45	0.122	118.16	13.48
		CNT4	8580	61	0.110	105.58	12.05
		CNT5	2512	78	0.026	25.05	2.86
			57,261	40	**0.823**	**789.36**	**90.05**
Chobe	22,550	CHB1	343	2	0.006	5.44	0.62
		CHB2	0	0	0.000	0.00	0.00
			343	2	**0.005**	**5.44**	**0.62**
Ghanzi	117,910	GHZ1	3446	42	0.041	38.93	4.44
		GHZ2	19,480	53	0.332	315.38	35.98
		GHZ3	19,764	27	0.322	304.75	34.77
			42,690	36	**0.608**	**659.07**	**75.19**
Kgalagadi	106,940	KLD1	8423	43	0.156	147.20	16.79
		KLD2	16,476	37	0.292	275.51	31.43
		KLD3	28,969	68	0.416	393.03	44.84
			53,868	50	**0.863**	**815.73**	**93.06**
Kgatleng	7960	KGT1	2894	70	0.047	45.80	5.23
		KGT2	1792	47	0.024	23.37	2.67
			4686	59	**0.075**	**69.17**	**7.89**
Kweneng	35,890	KWN1	9376	52	0.160	153.40	17.50
		KWN2	11,743	66	0.165	159.43	18.19
			21,119	59	**0.352**	**312.83**	**35.69**
Ngamiland	111,650	NGD1a	2198	9	0.037	35.40	4.04
		NGD1b	0	0	0.000	0.00	0.00
		NGD2	15,745	20	0.221	209.51	23.90
		NGD3a	0	0	0.000	0.00	0.00
		NGD3b	0	0	0.000	0.00	0.00
			17,943	16	**0.221**	**244.91**	**27.94**
North-East	5990	NED1	940	73	0.016	15.38	1.75
		NED2	1125	38	0.016	15.19	1.73
		NED3	638	37	0.009	8.28	0.94
			2703	45	**0.040**	**38.85**	**4.43**
South-East	1780	SED1	0	0	0.000	0.00	0.00
		SED2	278	20	0.004	3.74	0.43
			278	16	**0.005**	**3.74**	**0.43**
Southern	28,470	STN1	16,884	67	0.288	277.67	31.68
		STN2	2241	67	0.032	30.58	3.49
			19,125	67	**0.319**	**308.25**	**35.17**
	581,730		**220,016**	**38**	**3.311**	**3247**	**370.00**

North-East District (5990 km^2): Freehold farms constitute the major land use and occupy nearly half of the country's second smallest district [83]. Hill chains and active drainage systems in most areas of the district presented the biophysical constraint that excluded 111 km^2 of the district (Table 4). Commercial farms (2557 km^2), settlements and associated major infrastructural corridors (386 km^2), mostly in NED1 and NED2, arable land and artificial water bodies or dams exclude a total area of 3176 km^2, which was just more than half of the district surface area (Table 5). Since all the land was accessible, biophysical and land use constraints excluded a total of 3287 km^2 or nearly 55% of the land, thereby 2703 km^2 of the district land area for occupied by CSP infrastructure (Table 6) with a potential of 43.6 $TWhy^{-1}$or approximately 5.0 GW (Table 7).

South-East District (1780 km^2): The district is the most highly populated and most urbanized in the country [84]. It is also the only district which has the largest proportion of its area covered by rough terrain in the form of hills, which are the major biophysical constraints, followed by extensive drainage systems, most of which are in SED2, so that a total area of 102 km^2 was biophysically excluded (Table 4). Settlements and associated major infrastructural corridors, freehold farms, protected areas and recreational zones (52 km^2), arable land with mixed farming, and artificial water bodies in SED2, exclude an area of 1400 km^2 (Table 5). A combined total area of 1502 km^2 or more than 85% of the land was, therefore, excluded, so that only 278 km^2 of the land was available (Table 6), with an estimated CSP potential of approximately 4.7 $TWhy^{-1}$ or 500 MW (Table 7).

Southern District (28,470 km^2): The district has multiple and dedicated land uses in the form of commercial farms, settlements and associated major infrastructural corridors and arable land [85,86]. Hill chains in STN2 and active drainage systems in the eastern part of the district take up 134 km^2 of the district land area (Table 4). Commercial farms in STN1, arable land with mixed farming in both STN1 and STN2, settlements and associated major infrastructural corridors, the Jwana Game Park (190 km^2), artificial reservoirs, monuments and preserved historic sites as well as land devoted for future conservation in STN2 collectively excluded an area of 9211 km^2 (Table 5). Since there was no land considered inaccessible, a combination of both biophysical and land use constrained 9345 km^2, so that 19,125 km^2 or nearly two third of the land is available (Table 6). The district, therefore, was found to have enough available land to yield a CSP potential of an estimated 344.0 $TWhy^{-1}$ or 39.2 GW (Table 7).

5. Summary and conclusions

A bottom-up approach that makes use of a SolarGIS average annual DNI solar radiation map and a land exclusion criteria analysis was used to estimate the CSP technical potential of Botswana. The abundance of solar resource throughout the country and large tracts of unoccupied suitable land were found to be capable of providing opportunities for the deployment of dry-cooled PTC-type CSP technology as a cleaner and sustainable energy that could significantly reduce dependence on fossil energy sources. Dry-cooled PTC type CSP plants equipped with thermal

storage to overcome intermittencies of solar energy are recommended as the most cost-effective mature CSP technology to provide renewable energy for the country. Based on annual DNI solar radiation map values for the period 1994–2010 and land availability that takes into account the constraints imposed by physiographic features and land use, Botswana has a total of 220,016 km^2 of available land, which is enough to accommodate a CSP technical potential of 3189.54 $TWhy^{-1}$ or 363.86 GW, which represents approximately 0.06% of the total solar irradiance received countrywide. The Okavango Delta, the Makgadikgadi Salt Pans and the Kalahari active dune-fields were found to present the major natural land constraints to CSP deployment in the Ngamiland, Central and Kgalagadi districts respectively. Land use in the form of biodiversity conservation, wildlife protected areas, farms and agricultural land were found to be the major human-induced constraints to CSP land suitability, whilst natural barriers such as relief and drainage systems had a lesser effect. All the districts in the country have some potential sites for the location of CSP plants, with the Central and Ngamiland districts having most available land on account of their large surface area. The Kweneng District has the largest proportion of land available relative to its size for CSP deployment, particularly in the west where biophysical and land constraints are fewer. Botswana's technical CSP potential is nearly two-thirds that of neighbouring South Africa's 574.6 GW where biophysical and land use constraints significantly limit the geographical surface potential despite that the country is twice larger in terms of size. Despite the relatively high potential, the economic potential is expected to be lower when the CSP plants are constructed due to other factors that would come into play, such as the levelized cost of electricity (LCOE) due to the consideration of the capacity factor amongst other operational constraints. Nonetheless, the potential provides a baseline indicator to justify future investment in solar thermal electricity production as the country implements its climate change mitigation strategies in line with its sustainable development goals. Furthermore, the CSP potential values are expected to change in the future as more reliable high resolution solar radiation maps become available. Additional ground-based DNI measuring stations, more infrastructural developments in response to economic and population growth, advances in solar technology and changes in the environmental parameters due to climate change may affect the technical potential in the long term.

Acknowledgements

We thank the Department of Meteorological Services for providing long-term meteorological data for all the ten districts which was used in this research.

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